Comparative analysis of facies and reservoir characteristics of Miri Formation (Miri) and Nyalau Formation (Bintulu), Sarawak

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Abstract— This study on the sedimentological and reservoir petrophysical properties (porosity, permeability, density, sonic velocity) of sandstones were conducted on the sedimentary rocks belonging to the Miri Formation (Middle Miocene) from Miri and Nyalau Formation (Middle Miocene) from Bintulu in Sarawak. The objectives are i) to investigate and determine the facies characteristics and reservoir properties of the different types of sandstones, and ii) to establish the relationships between the facies characteristics and petrophysical properties. Two lithofacies have been sampled from the outcrops of Nyalau Formation and four lithofacies from the outcrops of Miri Formation based on lithology, sedimentary structures, fossil traces and bed geometry. These are grouped into four major lithofacies: (i) hummocky cross-stratified sandstones (HCS); (ii) trough cross-bedding sandstones (TCB); (iii) bioturbated sandstones; and (iv) swaley cross-stratified sandstones (SCS). Hummocky and swaley cross-stratified sandstones, trough cross-bedded sandstones and some bioturbated sandstones of Miri formation recorded the highest poro-perm values, with relatively lower density values (as compared Bintulu samples). The TCB sandstones are well sorted sandstones, with minimal mud content. This has contributed to the high poro-perm values. The bioturbated swaley cross-stratified sandstone (MF4) shows high permeabilities in some samples and low permeabilities in others. This reflects the heterogeneity in facies characteristics and poro-perm distribution of bioturbated samples.

Bioturbated HCS, the HCS and TCB sandstones of Bintulu show moderate poro-perm values. The Nyalau Formation rocks are older, and thus are expected to have undergone greater compaction than the younger Miri Formation. This is also reflected in the higher density values recorded for all the Bintulu samples.

Keywords: sedimentological properties, reservoir petrophysical properties, sandstone, Miri Formation, Nyalau Formation

INTRODUCTION

In general, facies characteristics determine the overall reservoir properties of sandstones, while diagenetic changes impose a secondary control on their poro-perm characteristics. The purpose of studying the reservoir sedimentological characteristics and petrophysical properties of Tertiary sandstones from Sarawak is to investigate and determine the facies characteristics, and reservoir properties of the different types of sandstones, and to establish the relationships between the facies characteristics and petrophysical properties.

This study on the sedimentological and reservoir petrophysical properties (porosity, permeability, density, sonic velocity) of sandstones were conducted on the sedimentary rocks belonging to the Miri Formation (Middle Miocene) from Miri and Nyalau Formation (Middle Miocene) from Bintulu in Sarawak.

GEOLOGICAL BACKGROUND

Miri Formation, Miri

The rocks exposed around the Miri city, Sarawak, which belongs to the Middle Miocene Miri Formation, are the uplifted part of the subsurface, oil-bearing sedimentary strata of the Miri oilfield and possibly also for the offshore fields.

Liechti *et al.* (1960) described the formation as a predominantly marine arenaceous succession, based on observations of outcrops of the Miri Anticline and examination of subsurface material from the Miri and the Seria oil field. The basal contact with the underlying Setap Shale Formation is a gradual transition from an arenaceous succession downward into a predominantly argillaceous succession. Based on lithological differences and small benthonic Foraminifera assemblage, Liechti *et al.* (1960) and Wilford (1961) divided the formation into a Lower and Upper unit.

The maximum total thickness of Miri Formation estimated in the Seria Field in Brunei is over 6,000 feet (1830 m). The difference between the Lower and the Upper Miri is not clear enough to map the boundary on lithology alone. The Lower Miri consists of well-defined beds of sandstones and shales, with the shales slightly prevailing. This lower unit passes out downwards into the underlying Setap Shale Formation. The Upper Miri Formation is more arenaceous. It consists of rapidly recurrent and irregular sandstone-shale alternations, with the sandstone beds passing gradually into clayey sandstone and sandy or silty shale. From the identification of marine microfauna and lithological characteristics, Liechti *et al.* (1960) concluded that these sediments were deposited in a littoral to inner neritic shallow marine environment.

Nyalau Formation, Bintulu

The Nyalau Formation (Middle Miocene) of Bintulu area, Sarawak occurred as (i) offshore-subtidal estuarine sandstones, sandy shales, and shales with dispersed lignite bands and marls, (ii) silty sandstone interval, which are partly calcareous, and grading into sandy-limestone, (iii) Biban sandstone Member, of Oligocene-Miocene age, which consists of fine- to medium-grained sandstones and siltstones with calcareous nodules and (iv) Kakus Member, of Lower-Middle Miocene age, consisting of massive sandstone intervals, laminated clays, and brackish-shales and lignites (Liechti *et al*., 1960; Kho, 1968).

METHODOLOGY

To achieve the objectives of the study, the following methods of investigations have been employed. These are:

i. Field sedimentological analysis, which include facies description;
ii. Collection of sandstone samples at selected outcrops;
iii. Laboratory petrophysical testing and measurements. These include grain size analysis, porosity analysis, permeability analysis and density measurements. The seismic velocity of some of the sandstone samples was also measured.

RESULTS AND DISCUSSION

Figure 1 shows the locations of Bintulu and Miri in Sarawak, East Malaysia. Figure 2 shows the outcrop of Miri Hillside Garden, showing the different lithofacies associations of Miri Formation in Miri, Sarawak. Figure 3 shows the different lithofacies associations at the outcrop of Bintulu New Airport, Nyalau Formation in Bintulu, Sarawak. Figures 4 and 5 are the stratigraphy logs of the outcrops.

Figures 6 to 8 show the relationship between permeability and porosity, density and porosity, velocity and porosity for different lithofacies. The grain size distribution pattern of some of the sandstone samples are shown in Figures 9a to 9d.

Sandstones from Miri Formation (Miri)

Facies Description

(A) Facies MF1: Parallel, low angle-to-hummocky cross-stratified sandstone, sparsely bioturbated

Facies MF1 is characterized by light grey, fine grained sandstone with parallel-to-hummocky cross-stratification.

Figure 1: Map of Sarawak, East Malaysia showing the study area of Bintulu and Miri.

Figure 2: Outcrop Miri Hillside Garden, showing the different lithofacies associations, Miri Formation in Miri, Sarawak.

Figure 3: Outcrop Bintulu New Airport, showing the different lithofacies associations, Nyalau Formation in Bintulu, Sarawak.

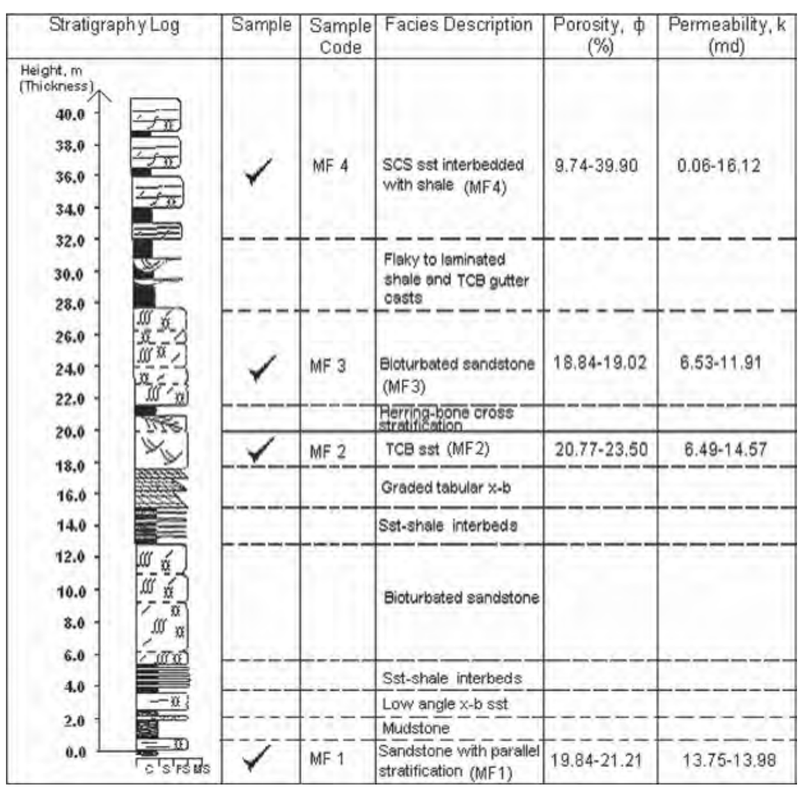

Figure 4: Sedimentological / stratigraphic log of the outcrop at Hillside Garden, Hospital Road, Miri town in Sarawak.

The average thickness of sandstone beds are around 0.9 m. The trace fossil Ophiomorpha is well distributed throughout the facies, while small Chondrites burrows are common near the top of this facies.

The interbedding of MF1 with mudstones reflects alternative fair-weather conditions, sediments fall-out, and combined, unidirectional and oscillatory, or pure oscillatory flows. The occurrence of hummocky bedforms clearly indicates a storm origin for the sandstone beds. Low angle and hummocky cross-stratification in sandstones can be produced by storm wave, which were deposited rapidly, probably below fair weather wave base (Leckie, 1988).

(B) Facies MF2: Trough cross-bedded sandstone

Facies MF2 is light yellowish-brown, fine-to-medium grained, very well to well sorted, sandstone bed dominated by low-angle to trough cross-bedding with average thicknesses around 2.5 ms. Mud and carbonaceous drapes are common.

Facies MF2 records deposition under tidal influence as evidenced by the presence of cross-stratification with mud drapes, reactivation surfaces, herringbone cross-bedding and flaser mud bedding. The trough cross-bedding can be classified as being formed by large compound dunes or sand waves migrating during high energy tidal current, with periods of slack water marked by mud drapes.

This facies is interpreted as stacked tidal channels and bars deposits that developed in the outer zone, estuary mouth, in a tide-dominated estuary (Abeida, 2005).

(C) Facies MF3: Bioturbated sandstone

Facies MF3 is composed of light grey, fine grained sandstone with massive (homogenized?) and bioturbated texture. Ophiomorpha traces occupy more than 50% in this facies. Thickness of sandstone bed is around 6.0 m. Remnant sedimentary structures include parallel stratification and carbonaceous layers.

Due to the reworking by bioturbation, there is no clear evidence of tidal or wave processes in this facies. The depositional process of this facies reflects low energy environment, which supports high organism activity. The occurrence of Ophiomorpha burrows suggests a sandy shallow marine setting. This facies is interpreted as a lower shoreface, probably just above fair-weather wave base.

(D) Facies MF4: Swaley cross stratified sandstone interbedded with shale/Amalgamated hummocky cross-stratified sandstone

Facies MF4 consists of light grey, fine grained sandstone bed with swaly cross-stratification, and low-angle cross-lamination. These sandstone beds show thicknesses exceeding 2.0 m. Mudstone layers and partings, up to 15 cm thick, separates these amalgamated hummocky cross-stratified units. Trace fossils are rare-to-common, dominated by Ophiomorpha, Skolithos and Chondrites.

Swaly cross-stratified sandstones form in settings where the deposition and preservation of mudstones are reduced, indicating a more agitated, wave and storm reworked and shallower environments compared to HCS. Leckie (1988) and Walker (1992) gave the name swaly cross stratification for sandstones thicker than 2.0 m, where only swales are preserved (Walker & Plint, 1992). These types of sandstones are generally preserved in the areas of weak tidal activity that is below fair-weather wave base (Walker & Plint, 1992).

Reservoir Petrophysical Properties

The sandstone samples were collected from the outcrop of Miri Formation for various petrophysical analysis and measurements. These samples were chosen based on lithofacies. Porosity, permeability, density and velocity were determined for four sandstone lithofacies: (i) facies MF1, (ii) facies MF2, (iii) facies MF3 and (iv) facies MF4.

(A) Facies MF1: Parallel, low angle-to-hummocky cross-stratified sandstone, sparsely bioturbated

Sample MF1 shows values 19.84-21.21% of porosity and the average porosity percentages is around 20%. Sample MF1 has average permeability value of ~14 md. This sample have densities of more than 2 g/cm^3; 2.07-2.16 g/cm^3. Velocities of sample MF1 are ranging from 2191-2472 m/s.

(B) Facies MF2: Trough cross bedding sandstone

Facies MF2 shows values 20.77-23.50% of porosity. Facies MR8 has permeability values which are ranging from 6.49-14.57 md. Samples of this facies have densities 1.86-2.04 g/cm^3. Average velocity of this facies is ~2000 m/s.

(C) Facies MF3: Bioturbated sandstone

Sample MF3 shows the value of porosity from 18.84-19.02%. Sample MF3 has a wide range of permeability values, ranging from 6.53-11.91 md. This sample have densities of more than 2 g/cm^3; 2.25-2.62 g/cm^3. Velocities of sample MF3 are dominated by values ranging from 2191-2806 m/s.

(D) Facies MF4: Swaley cross stratified sandstone interbedded with shale/Amalgamated hummocky cross-stratified sandstone

The porosity values of sample MF4 have a wide range values, which range 9.74-39.90%. This sample has also a wide range of permeability values, ranges 0.06-16.12 md. Sample MF4 have densities of more than 2 g/cm^3; 2.15-2.51 g/cm^3. Average velocity of sample MF4 is 1917 m/s.

Sandstones from Nyalau Formation (Bintulu)

Facies Description

(A) Facies BT-A: Well bioturbated mudstone and hummocky cross-stratified sandstone interbedding (Sample BT-4 and BT-5)

Facies BT-A is a well-bioturbated mudstone and sandstone interbedding interval. The sandstone is thin, with remnant hummocky cross-stratification sandstone and silty to fine grained. The thicknesses of the sandstones are approximately 1-1.5 m.

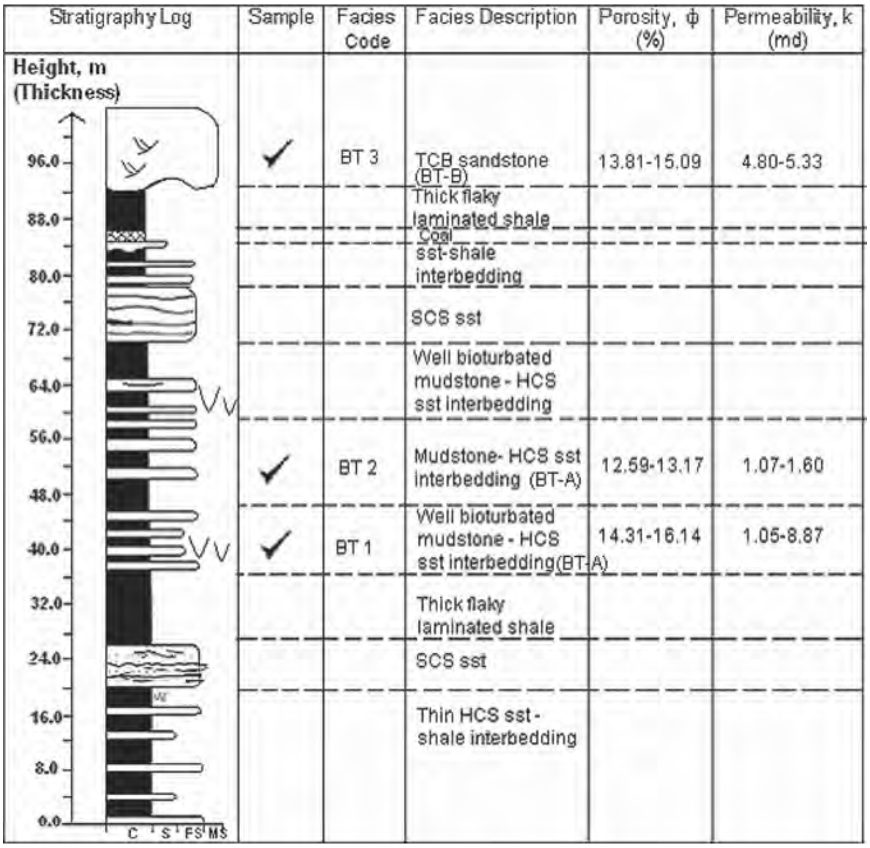

Figure 5: Sedimentological / stratigraphic log of the outcrop at Bintulu New Airport, in Bintulu, Sarawak.

Hummocky cross-stratification is interpreted to be one of the diagnostic sedimentary structures of storm-dominated shallow marine environment. Hummocky cross-stratified sandstones are generally preserved in areas of weak tidal activity that lie below fair-weather wave base (Walker, 1992). This facies is interpreted as lower-middle shoreface deposit.

(B) Facies BT-B: Trough cross-bedded sandstone (Sample BT11)

Facies BT-B is trough cross-bedded sandstone. The thickness of this facies is more than 8 m. This facies erosively overlies a black, carbonaceous mudstone unit.

Trough cross-bedding are formed due to the migration of three-dimensional dunes. Trough cross-bedded sandstones that comprises of fine- to medium-grained sand commonly formed as a result of three-dimensional dunes migration (Collinson, 1969). This facies is interpreted as a small, shallow tidal channel-fill.

Reservoir Petrophysical Properties

Eight sandstone samples were collected from an outcrop of the Nyalau Formation in Bintulu for various petrophysical analysis and measurements. These samples were chosen based on lithofacies. Porosity, permeability, density and velocity were determined for two sandstone lithofacies: (i) facies BT-A; (ii) facies BT-B.

(A) Facies BT-A: Well bioturbated mudstone and hummocky cross-stratified sandstone interbedding (Sample BT1)

The porosity values of sample BT4 are ranging from 14.31-16.14%. Sample BT4 has the permeability values which are ranging from 1.05-8.87 md. Sample BT4 have densities of more than 2 g/cm^3; 2.33-2.51g/cm^3. The average density is around 2.4g/cm^3. Velocities of sample BT4 are dominated by values ranging from 1524-3014m/s.

(B) Facies BT-A: Mudstone-hummocky cross stratified sandstone interbedding (Sample BT2)

Sample BT5 shows values 12.59-13.17% of porosity percentages. This sample has permeability values 1.07-1.6 md. Sample BT5 have densities of more than 2 g/cm^3; 2.35-2.37g/cm^3 and the velocities are ranging from 2453-2520 m/s.

(C) Facies BT-B: Trough cross bedding sandstone

Sample BT11 shows value 13.81-15.09% of porosity percentages. This sample has permeability values 4.8-5.33 md. Sample BT11 have densities of more than 2 g/cm^3; 2.05-2.07 g/cm3 and the velocity is around 1514 m/s.

Grain Size analysis

To determine the grain size of the sandstones, the sieving method was carried out on four samples taken from different localities (Miri and Bintulu). The sieving

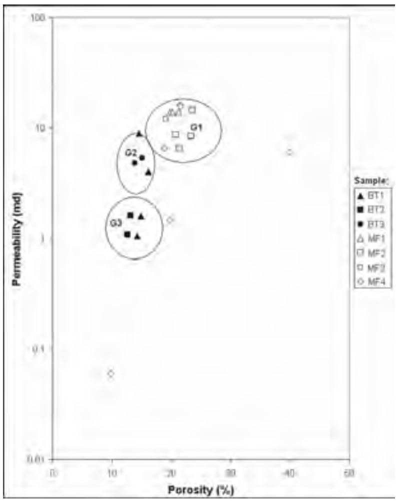

Figure 6: Permeability vs porosity cross-plot for sandstone samples from Bintulu (Nyalau Formation) and Miri (Miri Formation), Sarawak.

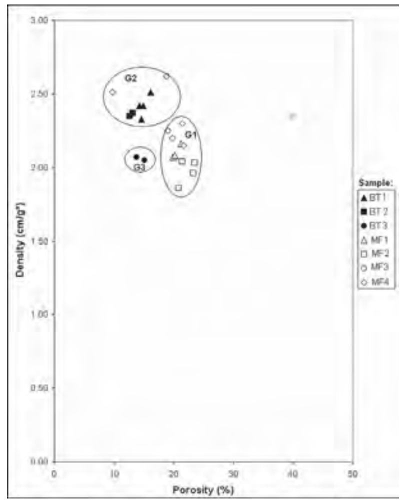

Figure 7: Density vs porosity cross-plot for sandstone samples from Bintulu (Nyalau Formation) and Miri (Miri Formation), Sarawak.

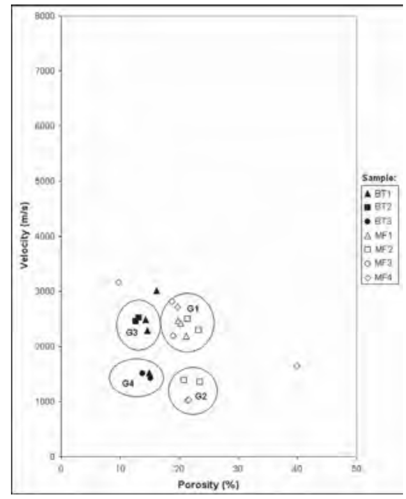

Figure 8: Velocity vs porosity cross-plot for sandstone samples from Bintulu (Nyalau Formation) and Miri (Miri Formation), Sarawak.

results of size analysis were plotted as a histogram which represents the distribution of grain sizes for the sandstones (Figures 9a-9d).

Miri Formation

The sieving method was carried out for two sandstone samples from Miri Formation. The samples were collected from facies MF2 and facies MF3.

(A) Facies MF2: Trough cross bedding sandstone

From Figure 9a, the sandstone sample from facies MF2 has the grain size in the range of the phi values 2.75-3.25, which according to Wentworth (1922), it is fine grain sandstone. The sorting for the sandstone from facies MF2 is with good sorting according the distribution pattern in Figure 9a.

(B) Facies MF3: Bioturbated sandstone

From Figure 9b, the sandstone sample from facies MF3 has the grain size of the phi value more than 4.00, which is siltstone to claystone. The sorting for the sandstone from facies MF3 is with poor sorting according the distribution pattern in Figure 9b.

Nyalau Formation

The sieving method was carried out for two sandstone samples from Nyalau Formation. The samples were collected from facies BT-A.

(A) Facies BT-A: Well bioturbated mudstone and hummocky cross-stratified sandstone interbedding (samples BT1 and BT2)

From Figure 9c, the sandstone sample BT1 has the grain size of the phi value more than 4.00, which is siltstone to claystone. The sorting for the sandstone from facies BT-A is with poor sorting and slightly bimodal according the distribution pattern in Figure 9c. The coarser mode may have been introduced by the bioturbation.

From Figure 9d, the sandstone sample BT2 has the grain size of the phi value is approximately >4.00, which is siltstone to claystone. The sorting for the sandstone from facies BT2 is with poor sorting according the distribution pattern in Figure 9d.

Relationships of porosity vs permeability, density and velocity

Although the absolute permeability and velocity values for the different facies are generally low, but the differences and relative values reflect the relative reservoir quality of the different facies. These permeability values may be inherited due to the technique used, i.e. nitrogen permeability equipment. Sandstone velocities are normally within range (1300-7000 m/s). The values measured are markedly lower than the minimum standard value for sandstones or the water velocity (1500 m/s). The error recorded is probably due to faults in the equipment while the experiment was carried out.

Figure 6 shows the permeability vs porosity cross-plot for sandstone samples Miri (Miri Formation) and Bintulu (Nyalau Formation) in Sarawak. The sandstones belonging to the Miri and Nyalau Formation show a more dispersed porosity-permeability relationships. These sandstones formed three groups - high porosity, good permeability (sample MF1, MF2, MF3), good porosity, good permeability group (samples BT4, BT11) and low porosity- low permeability group (samples BT1, BT2). Sample MF4, bioturbated SCS sandstone, do not show any specific trend.

Figure 7 shows the density vs porosity cross-plot for sandstone samples Miri (Miri Formation) and Bintulu (Nyalau Formation) in Sarawak. The sandstones belonging to the Miri and Nyalau Formation show a more dispersed porosity-density relationships. These sandstones formed three groups. Group one is with low density, around 2 g/

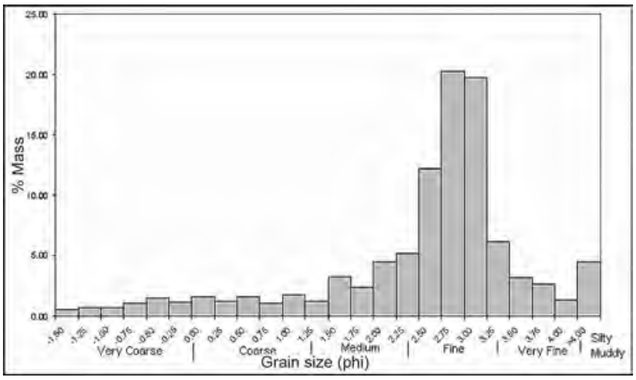

Figure 9a: Histogram for trough cross-bedding sandstone from Miri Formation, Miri.

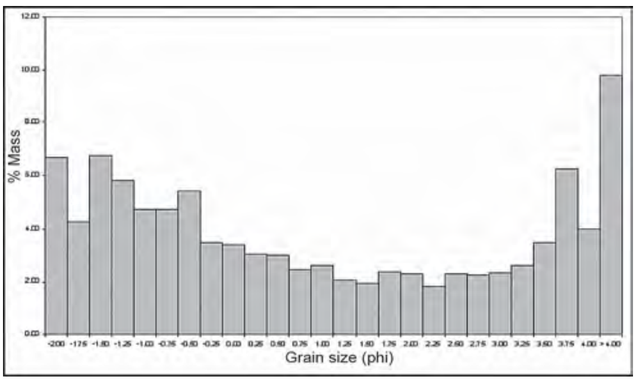

Figure 9b: Histogram for bioturbated sandstone from Miri Formation, Miri.

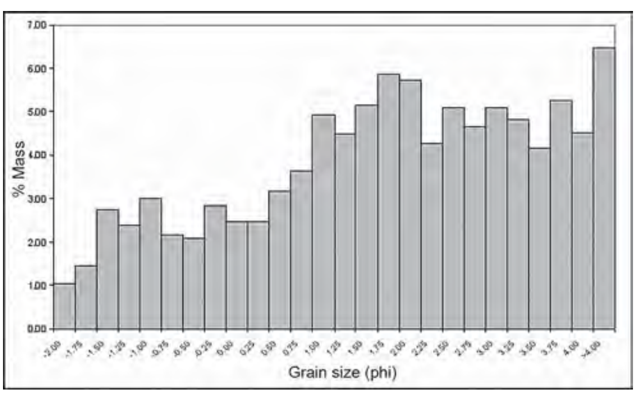

Figure 9c: Histogram for well bioturbated mudstone and hummocky cross-stratified sandstone interbedding, facies BT1, Nyalau Formation.

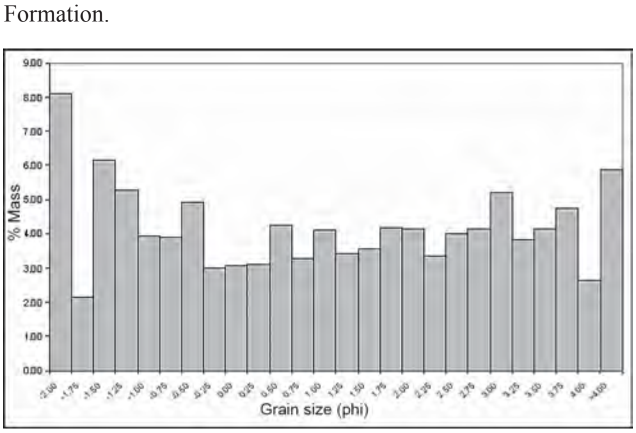

Figure 9d: Histogram for mudstone-hummocky cross stratified sandstone interbedding, facies BT2, Nyalau Formation.

cm³ and high porosity, around ~20% (all samples for Miri Formation). Group two is with high density which is around ~2.50 g/cm³ and moderate porosity ~15% (samples for Nyalau Formation, sample BT1 and BT2). Group three has low density ~2 g/cm³ and moderate porosity ~15% (sample BT3 from Nyalau Formation).

Figure 8 shows the velocity-porosity cross-plot for sandstone samples from Miri Formation (Miri) and Nyalau Formation (Bintulu) in Sarawak. The plot shows a more dispersed porosity-velocity relationships. The samples can be grouped into four groups. Group 1 (G1) and group 2 (G2) are samples from Miri Formation while group 3 (G3) and group 4 (G4) are samples from Nyalau Formation. Group one (G1) is with high porosity, moderate velocity (samples MF1, MF2, MF3 and MF4); group 2 (G2) is with high porosity, low velocity (samples MF2 and MF4); group 3 (G3) shows moderate porosity, moderate velocity (samples BT1 and BT2); and group 4 (G4) shows moderate porosity, low velocity (samples BT1 and BT3). The samples MF2 and MF3 from Miri Formation are represented in both groups (G1 and G2). Velocity values of sample BT4 from Nyalau Formation are widely scattered.

CONCLUSION

Two lithofacies have been sampled from the outcrops of Nyalau Formation and four lithofacies from the outcrops of Miri Formation, based on lithology, sedimentary structures, fossil traces and bed geometry. These are grouped into four major lithofacies: (i) hummocky cross-stratified sandstones; (ii) trough cross-bedding sandstones; (iii) bioturbated sandstones; and (iv) swaley cross-stratified sandstones.

The cross-plots of porosity-permeability, porosity-density and porosity-velocity for all the samples are shown in Figures 6, 7 and 8.

Samples MF1, MF2 and MF3 of Miri formation recorded the highest poro-perm values, with relatively lower density values (as compared to BT1 and BT2 of Bintulu) and widely distributed velocity values. The MF2 and MF4 are better sorted sandstones, with minimal mud content. This has contributed to the high poro-perm values. The bioturbated swaley cross-stratified sandstone (MF4) shows high permeabilities in some samples, and suppressed, low permeabilities in other samples. This reflects the heterogeneity in facies characteristice and poro-perm distributions of bioturbated samples.

Bioturbated HCS, the HCS and TCB sandstones of Bintulu (BT1, BT2 and BT3) show moderate poro-perm values. The Nyalau Formation rocks are older, and thus are expected to be more compacted than the Miri Formation. This is also reflected in the higher density values recorded for all the Bintulu samples.

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